

Threshold Studies of Charm Mixing and Strong Phases with CLEO-c

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1 Introduction

Charm mixing in the Standard Model is described by the parameters $x \equiv 2(M_2 - M_1)/(\Gamma_2 + \Gamma_1)$ and $y \equiv (\Gamma_2 - \Gamma_1)/(\Gamma_2 + \Gamma_1)$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths, respectively, of the neutral D meson CP eigenstates, D_1 (CP -odd) and D_2 (CP -even): $|D_{1,2}\rangle \equiv (|D^0\rangle \pm |\bar{D}^0\rangle)/\sqrt{2}$. Recently, several experiments have directly probed x and y [1, 2, 3, 4, 5, 6, 7], as well as the “rotated” parameters $y' \equiv y \cos \delta - x \sin \delta$ and $x' \equiv y \sin \delta + x \cos \delta$ [8, 9, 10], where $-\delta$ is the relative phase between the doubly Cabibbo-suppressed $D^0 \rightarrow K^+\pi^-$ amplitude and the corresponding Cabibbo-favored $\bar{D}^0 \rightarrow K^+\pi^-$ amplitude: $\langle K^+\pi^-|D^0\rangle/\langle K^+\pi^-|\bar{D}^0\rangle \equiv re^{-i\delta}$. We adopt a convention in which δ corresponds to a strong phase, which vanishes in the $SU(3)$ limit [11]. In this article, we update an analysis [12] that gave the first direct determination of $\cos \delta$ using correlated production of D^0 and \bar{D}^0 mesons in e^+e^- collisions produced at the Cornell Electron Storage Ring and collected with the CLEO-c detector. Here, we also present a first measurement of $\sin \delta$.

At the $\psi(3770)$ resonance, the $D^0\bar{D}^0$ system is produced in an overall charge conjugation eigenstate with $C = -1$. As a result of this quantum coherence, the exclusive $D^0\bar{D}^0$ decay rate to a final state $\{i, j\}$, where i and j label the final states of the two D mesons, is given by the square of the antisymmetric amplitude

$$\Gamma(i, j) \propto \mathcal{M}_{ij}^2 \equiv \left| \langle i|D^0\rangle\langle j|\bar{D}^0\rangle - \langle i|\bar{D}^0\rangle\langle j|D^0\rangle \right|^2 + \mathcal{O}(x^2, y^2), \quad (1)$$

where the $\mathcal{O}(x^2, y^2)$ term represents a mixed amplitude. These exclusive rates depend on the mixing parameters and amplitude ratios defined above:

$$\Gamma(i, \bar{j}) = \Gamma(\bar{i}, j) \propto 1 + r_i^2 r_j^2 - 2r_i \cos \delta_i r_j \cos \delta_j - 2r_i \sin \delta_i r_j \sin \delta_j \quad (2)$$

$$\Gamma(i, j) = \Gamma(\bar{i}, \bar{j}) \propto r_i^2 + r_j^2 - 2r_i \cos \delta_i r_j \cos \delta_j + 2r_i \sin \delta_i r_j \sin \delta_j. \quad (3)$$

Inclusive rates are obtained by summing over exclusive rates and are trivially related to the branching fractions (\mathcal{B}) in uncorrelated decay:

$$\Gamma(i, X) = \sum_j [\Gamma(i, j) + \Gamma(i, \bar{j})] = \mathcal{B}_i + \mathcal{B}_{\bar{i}} \propto 1 + 2yr_i \cos \delta_i + r_i^2. \quad (4)$$

By comparing correlated and uncorrelated decay rates, we extract simultaneously the charm mixing and strong phase parameters, as well as the number of $D^0 \bar{D}^0$ pairs produced (\mathcal{N}) and the branching fractions of the reconstructed D^0 final states.

Compared to our previous analysis [12], this update uses a dataset three times larger (818 pb^{-1}), and we reconstruct more CP eigenstates, as well as semimuonic D^0 decays and modes that provide sensitivity to $\sin \delta$ and r .

2 Experimental Technique

We reconstruct the D meson final states listed in Table 1. Following Ref. [13], the $K_S^0 \pi^+ \pi^-$ Dalitz plot is divided into eight bins according to the strong phase of the decay amplitude. Because CP eigenstates and semileptonic final states have known values of r_i and δ_i , they act as reference points for determining y and the strong phase δ in the $K\pi$ final state. Inclusive rates are derived from yields of single tags (ST), or individually reconstructed D^0 or \bar{D}^0 candidates. For exclusive rates, we reconstruct $D^0 \bar{D}^0$ pairs or double tags (DT).

Fully reconstructed modes are identified using two kinematic variables: the beam-constrained candidate mass $M \equiv \sqrt{E_0^2/c^4 - \mathbf{p}_D^2/c^2}$ and the energy difference $\Delta E \equiv E_D - E_0$, where \mathbf{p}_D and E_D are the total momentum and energy of the D candidate, respectively, and E_0 is the beam energy. We measure ST yields for all fully reconstructed modes except $K_S^0 \pi^+ \pi^-$. Decays with K_L^0 mesons and neutrinos, which we do not detect directly, are identified with a partial reconstruction technique, where the presence of the undetected particle is inferred via conservation of energy and momentum. We form DT candidates from all combinations of modes in Table 1,

| Type | Reconstruction | Final States | r_i | δ_i |
|--------------|----------------|--|----------|------------|
| Mixed- CP | Full | $K^- \pi^+, K^+ \pi^-, K_S^0 \pi^+ \pi^-$ | From fit | |
| $CP+$ | Full | $K^+ K^-, \pi^+ \pi^-, K_S^0 \pi^0 \pi^0$ | 1 | π |
| $CP+$ | Partial | $K_L^0 \pi^0, K_L^0 \eta, K_L^0 \omega$ | 1 | π |
| $CP-$ | Full | $K_S^0 \pi^0, K_S^0 \eta, K_S^0 \omega$ | 1 | 0 |
| $CP-$ | Partial | $K_L^0 \pi^0 \pi^0$ | 1 | 0 |
| Semileptonic | Partial | $K^- \{e^+, \mu^+\} \nu_{e,\mu}, K^+ \{e^-, \mu^-\} \bar{\nu}_{e,\mu}$ | 0 | — |

Table 1: D final states reconstructed in this analysis.

both Cabibbo-favored and Cabibbo-suppressed, with at most one missing particle. In addition, we reconstruct $\{K e \nu_e, K_L^0 \pi^0\}$, which has two missing particles, using the technique described in Refs. [14, 15].

3 Results

We combine 261 yield measurements, along with estimates of efficiencies and background contributions, in a least squares fit that determines 51 free parameters, including the five charm mixing and $D \rightarrow K\pi$ amplitude parameters listed in Table 2. The other parameters, for which the fit results are not shown, are \mathcal{N} , amplitude ratios and phases for the 8 phase bins in $K_S^0 \pi^+ \pi^-$, and 21 branching fractions. The fit includes both statistical and systematic uncertainties on the input measurements. We separate the statistical and systematic uncertainties in Table 2 by repeating the fit with only statistical uncertainties on the inputs. We perform one fit with no external inputs (Standard Fit) and another including the external measurements of y , x , r^2 , y' , and x'^2 compiled in Refs. [16, 17] (Extended Fit). In the Standard Fit, there is a sign ambiguity for $\sin \delta$, which is resolved in the Extended Fit. Because we treat uncertainties on external measurements as systematic uncertainties, when a fit parameter is directly constrained by an external measurement, we quote only one uncertainty in Table 2; in these cases, the statistical uncertainty effectively vanishes.

In the Standard Fit, the statistical uncertainties on y and $\cos \delta$ are roughly three times smaller than in our previous analysis [12]. The Extended Fit demonstrates that our measurements of $\cos \delta$ and $\sin \delta$ can be used to improve the uncertainty on y (by combining y and y' from other experiments) by approximately 10%, compared to the current world average found in Ref. [17]: $y = 0.79 \pm 0.13$.

Asymmetric uncertainties are determined from the posterior probability distribution functions (PDFs) shown in Fig. 1. These curves are obtained by re-minimizing

| Parameter | Standard Fit | Extended Fit |
|---------------|----------------------------------|----------------------------------|
| y (%) | $4.2 \pm 2.0 \pm 1.0$ | 0.636 ± 0.114 |
| r^2 (%) | $0.533 \pm 0.107 \pm 0.045$ | 0.333 ± 0.008 |
| $\cos \delta$ | $0.81^{+0.22+0.07}_{-0.18-0.05}$ | $1.15^{+0.19+0.00}_{-0.17-0.08}$ |
| $\sin \delta$ | $-0.01 \pm 0.41 \pm 0.04$ | $0.56^{+0.32+0.21}_{-0.31-0.20}$ |
| x^2 (%) | $0.06 \pm 0.23 \pm 0.11$ | 0.0022 ± 0.0023 |

Table 2: Results from the Standard Fit and the Extended Fit for all parameters except branching fractions. Uncertainties are statistical and systematic, respectively. In the Extended Fit, we quote only one uncertainty for y , r^2 , and x^2 , which are directly constrained by an external measurement.

the χ^2 at each point and computing $\mathcal{L} = e^{-(\chi^2 - \chi_{\min}^2)/2}$. We construct the PDFs for δ by scanning $\cos \delta$ and $\sin \delta$ under the constraint $\cos^2 \delta + \sin^2 \delta = 1$, which result in implied values for δ of $|\delta| = (10_{-53}^{+28+13})^\circ$ for the Standard Fit and $\delta = (18_{-17}^{+11})^\circ$ for the Extended Fit.

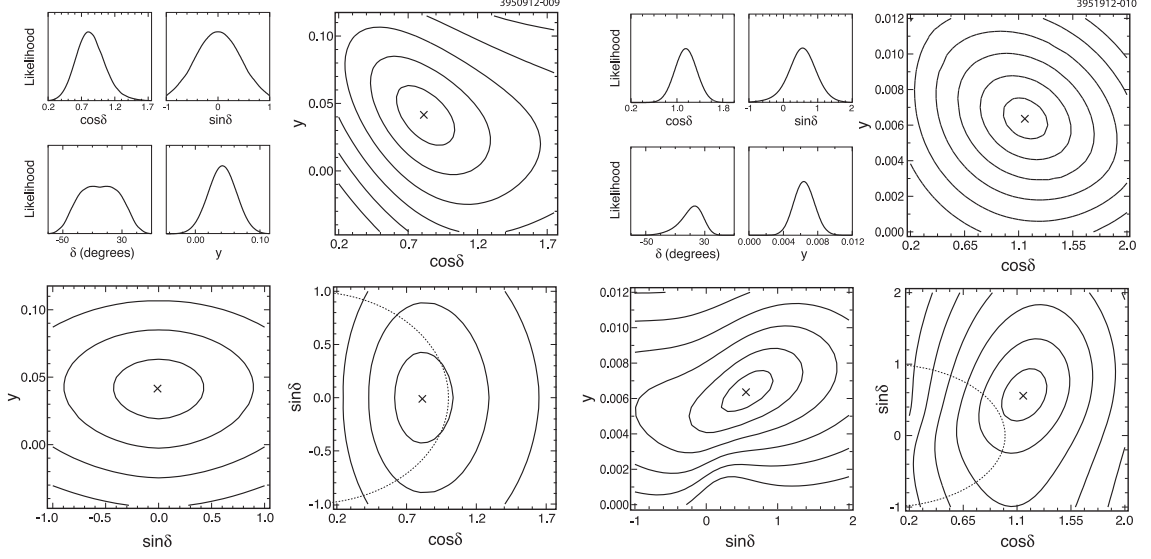


Figure 1: Likelihoods for the Standard Fit (left) and Extended Fit (right) including both statistical and systematic uncertainties for $\cos \delta$, $\sin \delta$, δ , and y . The two-dimensional likelihoods are shown as solid contours in increments of 1σ , where $\sigma = \sqrt{\Delta\chi^2}$. The dashed contour marks the physical boundary, where $\cos^2 \delta + \sin^2 \delta = 1$.

4 Summary

We present an updated analysis of charm mixing and the $D \rightarrow K\pi$ strong phase using quantum correlations in $D^0\bar{D}^0$ decays at the $\psi(3770)$ resonance. These results are based on the full CLEO-c dataset, and they make a significant contribution to the world averages of mixing parameters.

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